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Application of Cathodic Protection to Prestressed Concrete Bridges

Ministry of Transportation and Communications
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Abstract:	This project was undertaken to investigate the practicality and safety of applying cathodic protection to prestressed concrete structures. It is known that over-protection in a cathodic protection system can cause hydrogen evolution at the cathode. Hydrogen evolution adjacent to prestressing steel is unacceptable because it may contribute to embrittlement of the steel. Tests were carried out on full size laboratory specimens simulating typical prestressed and post-tensioned bridge members. Current and potential distribution were examined as cathodic protection was applied to the specimens. Both imbedded probes and surface half-cells were used to monitor the beams. Tests results indicated that cathodic protection of the deck steel in the post tensioned beam had no adverse effect on the post tensioning strands under normal operating conditions. It was found that cathodic protection could not be used to protect the post tensioned strands in the post tensioned beam when the metal duct containing the strands was electrically connected to the reinforcing steel. At applied current densities of less than 20 mA/m^2 on the surface of the prestressed beam, the maximum potential shifts measured on the prestressing steel were not more than 200 mV CSE. Current distribution along the length of the tendons was not uniform. A small scale laboratory test was undertaken to determine the polarized potential level necessary for the onset of hydrogen evolution. Under the conditions of the relatively crude experiment carried out, hydrogen evolution was found to occur at a potential of -0.85 V CSE.
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Table of Contents

1/ Introduction	1
1.1/ Problem	1
1.2/ Objective	1
1.3/ Background	1
2/ Test Program	2
2.1/ Post Tensioned Beam	2
2.2/ Pretensioned Beam	4
2.3/ Hydrogen Evolution	6
3/ Results and Discussion	7
3.1/ General Note	7
3.2/ Post Tensioned Beam	7
3.3/ Pretensioned Beam	9
4/ Conclusions	16
References	16

List of Tables

1/ Post Tensioned Beam – Potential Shift	17
2/ Pretensioned Beam, Tests 1 to 6 – Average Probe Current	18
3/ Pretensioned Beam – Relationship Between Probe Current and Applied Current	19

List of Figures

1a/ Post Tensioned Beam – Schematic Drawing, Elevation and Side View 20

1b/ Post Tensioned Beam – Reinforcement Cage 20

2/ Post Tensioned Beam – Current Probe 21

3/ Post Tensioned Beam – Complete Beam 21

4a/ Pretensioned Beam – Schematic Drawing, Elevation 22

4b/ Pretensioned Beam – Schematic Drawing, Sections 1-1 and 2-2 22

4c/ Pretensioned Beam – Reinforcement Cage 23

5/ Pretensioned Beam – Current Probe 23

6/ Pretensioned Beam – Complete Beam 24

7/ Cross-section of Cell used for Determination of Hydrogen Evolution 24

8/ Test Arrangements for Determination of Hydrogen Evolution 25

9/ Post Tensioned Beam – E log I Curve 25

10/ Post Tensioned Beam, Electrically Isolated Duct – Probe Currents 26

11/ Post Tensioned Beam – Electrically Isolated Duct – Relationship Between Probe Current and Applied Current 26

12/ Post Tensioned Beam, Electrically Connected Duct – Duct Current 27

13/ Pretensioned Beam, Test No. 1 – E log I Curve 27

14/ Pretensioned Beam, Test No. 1 – Probe Currents 28

15/ Pretensioned Beam, Test No. 1 – Potential Measurements Along a Vertical Line Down the South Side of the Beam 28

16/ Pretensioned Beam, Test No. 1 – Potential Measurements Along Profiles of Current Probes on Both Sides of the Beam 29

17/ Pretensioned Beam, Test No. 4 – Probe Currents 29

18/ Pretensioned Beam, Test No. 5 – Probe Currents 30

19/ Pretensioned Beam, Test No. 5 – Potential Measurements Along Profiles of Current Probes on Both Sides of the Beam 30

20/ Pretensioned Beam, Test No. 6 – Probe Currents 31

21/ Pretensioned Beam, Test No. 7 – Probe Currents 31

22/ Evolution Rate of Hydrogen Gas 32

1. INTRODUCTION

1.1 Problem

It is known that overprotection in a cathodic protection system can cause hydrogen evolution at the cathode and the potential at which hydrogen is formed is a function of the pH of the cathode environment. Hydrogen evolution adjacent to prestressing steel is totally unacceptable because of the ensuing embrittlement of the steel. The main problem, therefore, which applies to both pretensioned and post-tensioned prestressed bridges, is to determine whether or not it is safe, as far as the prestressing steel is concerned, to apply cathodic protection to the deck reinforcing steel. The secondary problem is to determine whether or not it is possible to apply cathodic protection to the prestressing steel per se and here the influence of the cable ducts is a consideration in post tensioned system.

1.2 Objective

The purpose of this investigation was:

1. To determine if cathodic protection of bridge deck systems has an adverse effect on the performance of the prestressing system

2. To determine if cathodic protection can be used to protect prestressing steel from corrosion

1.3 Background

It has previously been found that hydrogen evolution occurs at potentials from -0.97 V CSE to -1.17 V CSE for pH values from 4.0 to 12.5 respectively (1). Tests at FHWA showed that the bottom mat of a typical bridge deck received only about 13 % of the current density received by the top mat of steel (2). It is unlikely, therefore, that sufficent current would go to prestressing steel from a deck cathodic protection system to affect significantly the bond characteristics of the prestressing system. It seems, therefore, that the problem of hydrogen embrittlement caused by hydrogen evolution is the problem which should be addressed if cathodic protection of prestressed bridges is to be used with confidence.

2. TEST PROGRAM

2.1 Post tensioned beam

2.1.1 Test Specimen

A reinforced concrete post-tensioned beam 0.9 x 0.6 x 2.0 m was constructed. The beam contained a metal duct to accommodate the post tensioning steel. Reinforcement for the beam consisted of a double layer of 15 mm diameter reinforcing steel near the top to represent typical deck steel. This deck steel was supported at each corner by a single vertical length of 15 mm diameter reinforcing steel. A 75 mm concrete cube was used as a chair beneath each support. The reinforcing steel was welded at every intersection point to ensure electrical continuity and three separate ground connections were made to the upper steel layer with 14 gauge wire. The metal duct was a 57 mm diameter semi rigid post tensioning duct and was placed through holes in the beam end form. A bar was inserted through this duct to prevent bending of the duct during concrete placement. The duct was not connected electrically to the reinforcing steel. Details of the reinforcement are given in Figure 1.

The beam was cast on October 19, 84 and cured under wet burlap for 28 days. Following the curing period an anode was placed on the top surface of the beam. The primary anode consisted of a platinum wire, embedded in conducting polymer, running the full length of the beam. After the polymer had cured the entire top surface was painted with a proprietary brand of conducting paint with the exception of the areas immediately adjacent to two lifting hooks and six 100 x 100 mm spaces. These spaces were left unpainted to permit the placement of half cells for potential measurements of the rebar mat.

At 21 days age seven precast current pick-up probes were placed in the duct. Each probe consisted of 160 mm of 15 mm diameter steel rod with a 14 gauge lead wire firmly attached to one end. This probe was then cast in a 37 mm diameter cylinder of mortar, with w/c of 0.45. Each probe was connected by a shunt to a common ground wire on the control panel of a switch box. The resistor was chosen so that its resistance was less than 10 % of the open circuit AC resistance between the anode and the probe. During testing, a second ground wire was connected to the deck steel at the negative terminal of the rectifier. A probe is shown in Figure 2.

Current probe #4 had 2 % calcium chloride dihydrate by mass of cement admixed in the mortar jacket. This probe was, therefore, anodic to the reinforcing steel and acted as a macrocell. This macrocell was used to determine whether the corrosion of this cell could be halted by the application of current to the cathodic protection system.

The duct was fully grouted after placement of current probes. The grout used had a w/c of 0.45, with water reducing and aluminum powder admixtures.

The complete beam is shown in Figure 3. It was kept wrapped in a polythene sheet at all times except during actual testing. The sides of the beam were wetted periodically with water.

2.1.2 Test procedure

Two sets of tests were performed. In the first test, the post tensioning duct was electrically isolated from the deck steel and current probes. In the second test, the duct was electrically connected through a small resistor to the deck steel and current probes.

The cathodic protection system was powered with fully rectified unfiltered DC current and instant off potentials were measured using equipment similar to that described by Stratfull for E log I testing (2).

Current to the anode (applied current), current received by the current probes (probe current), and current received by the duct (duct current) were measured as the potential drops over the shunts incorporated in the circuits. All potentials were measured using high impedance voltmeters (10 megohms or better) with sensitivity of 1 μV.

Instant off potentials of the deck steel were measured using a copper-copper sulfate half cell which was permanently placed on the unpainted space at the top surface of the beam where the open circuit steel potential was most negative. Instant off potentials were also measured along the profile of the current probes on the side of the beam by placing another copper-copper sulfate half cell opposite to the current probes. The half cells were connected individually to an oscilloscope when the potential measurements were made.

Test results of a pilot program showed that it took some few minutes for stabilization to occur following current increments to the anode. This was mainly due to the capacitance and polarization effects of the system.

Consequently all the current and potential measurements were taken 15 minutes after each current increment.

2.2 Pretensioned beam

2.2.1 Test specimen

A pretensioned beam was constructed and consisted of a 0.2 x 0.6 x 3.5 m rectangular reinforced deck slab and a Type CPCI 1200 girder. Both deck and girder were cast monolithically.

Reinforcement comprised a double layer of 15 mm diameter reinforcing steel representing the deck steel in the slab, and 26 prestressing strands and 13 stirrups at variable spacing in the girder. This pattern of reinforcement was identical to that in a full size beam except the number of stirrups and the beam length was reduced.

In addition 35 current pick-up probes were used to replace three of the prestressing strands. The probes were 160 mm of 15 mm diameter steel rods spaced on 300 mm centres and attached to three 20 mm wide plastic strips using nylon ties except for probes #17, 18, and 19 on the middle row which were spaced on 380 mm centres. The steel in the probes had the same mass as the strands which they replaced. Each probe was connected by a 14 gauge lead wire and shunt to a common ground wire on the control panel of a switch unit. A separate ground wire attached to the deck steel was connected at the negative terminal of a rectifier when testing.

The reinforcing steel was welded at each steel intersection point and three separate ground connections were provided to the upper deck steel layer. Details of the reinforcing steel and beam dimensions are given in Figure 4 and a probe is shown in Figure 5.

The beam was poured on February 19, 85 and cured under wet burlap for 28 days. An anode was then placed on the top surface of the beam using the procedure described in Section 2.1.1. Again, the beam was wrapped in a polythene sheet and the sides of the beam were wetted intermittently. Figure 6 shows the complete beam.

In order to examine the effectiveness of cathodic protection for prestressing strands, various anode arrangements were made on the side(s) of the beam at later test stages. These arrangements will be described in Section 2.2.2.

2.2.2 Test procedure

Methods used to measure current and instant off potential were the same as that described in Section 2.1.2.

Seven sets of tests were performed at different test stages:

1. The anode located on the top surface of the beam was powered. Applied current and probe currents were measured. Instant off potentials were measured at the top surface of the beam, along the profiles of the three rows of current probes on the south side only or on both sides of the beam, and along a vertical line down the south side of the beam.

2. An 50 mm wide anode strip, which was identical to the primary anode mentioned in Section 2.1.1, was placed along the profile of the middle row of current probes on the north side of the beam. This side strip was then powered and applied current and probe currents were measured. Instant off potentials were measured at the top surface of the beam and along the profiles of the current probes on the south side (unpowered side) of the beam.

3. The anode in Test 2 was covered by conducting paint. The painted anode areas was extended to 50 mm on each side of the upper and lower rows of the current probes. This anode was powered and applied current and probe currents were measured. Instant off potentials were measured at the top surface of the beam, along the profiles of the probes on the south side, and along a vertial line down the south side of the beam.

4. The entire north side of the girder was covered by conducting paint. The anode was powered. Current and potential measurements were made as described in Test 3.

5. The anode on the top surface of the beam and the anode on the whole north side of the girder were powered simultaneously. Current and potential measurements were performed as described in Test 1. The potential measurements on the north side were obtained by placing the half cell on the predrilled 25 mm diameter holes opposite to the current probes.

6. Both north and south sides and two end faces of the girder were covered by conducting paint. The entire anode area was powered and applied current and probe currents were measured. Instant off potentials were measured at the top surface of the beam.

7. The anode in Test 6 and that on the top surface of the beam were powered simultaneously. Current and potential measurements were taken as described in Test 6.

Test 1 was primarily used to examine the danger of hydrogen evolution at the prestressing strands when cathodic protection was provided for the deck steel. Tests 2 to 7 were designed to study the feasibility of the application of cathodic protection to prestressing strands.

2.3 Hydrogen evolution

2.3.1 Test specimen

The test specimen used for the determination of the onset of hydrogen evolution consisted of a cathode and an anode. The cathode was a 125 mm length of 75 mm diameter steel pipe covered with a 1 mm layer of cement paste. The anode, which was located at the centre of the cathode, was made of a 150 mm length of 12 mm diameter mild steel bar. The surface of the steel was machine polished. A copper copper sulfate half cell was placed between the anode and cathode and was used as a reference electrode. Figure 7 shows the test specimen.

The test specimen was placed in 125 mm depth of saturated lime water inside a glass container. Four lead wires were brought out of the container, two for half cell measurements and two for unfiltered DC power. Provision was made to obtain air samples from above the lime water. The test arrangement is given in Figure 8.

2.3.2 Test procedure

This test was used to study the instant off potential level necessary for the onset of hydrogen evolution.

Fully rectified unfiltered DC current was applied to the cathode through the centre anode. Applied current and instant off potential measurements were made using the methods described in Section 2.1.2.

The critical potential range for the onset of hydrogen evolution was initially estimated by examining the E log I curve of the test specimen and by observing the bubble formation on the cathode surface. It was found that hydrogen gas was formed at about -1.0 V CSE. Consequently, current was applied to the system starting from about -700 mV CSE and was increased gradually by small increments. A gas sample was collected several hours after each current

increment. The sample was then tested for the presence of hydrogen gas by means of gas chromatography.

3. RESULTS AND DISCUSSION

3.1 The following section discusses applied currents in terms of both total current density and probe current densities. Probe current densities have been calculated by dividing the measured current flowing to each probe by the surface area of the probe. The current density applied to the system however, was based on the concrete surface covered by the anode rather than on the total surface area of imbedded reinforcing steel. This inconsistency is necessary because it is not possible to determine accurately the area of steel which actually receives current. Therefore, although both current densities are expressed in units of mA/m^2, it is not possible to directly compare the two.

Notwithstanding the above, in some of the tables and figures (specifically Tables 2 and 3 and Figures 10, 11, 12, 14, 17, 18, 20 and 21) the probe current density has been expressed as a percentage of the applied anode current density. This was done to show the characteristic relationship between the different probe current densities but it must be realized that the actual percentage values have no physical significance.

3.2 Post tensioned beam

3.2.1 Test 1 - Electrically isolated duct

Figure 9 shows the E log I curve for the instant off potential of the deck steel and applied current. The curve levelled off when the current and potential reached about 1 A/m^2 and -1.2 V CSE respectively. Theoretically, this `flat' portion represents hydrogen evolution stage of the system. Formation of hydrogen gas, however, may occur prior to these current and potential levels. The linear portion of the curve extended up to about 200 mA/m^2. Hydrogen evolution, therefore, was unlikely to occur when the current level was below 200 mA/m^2. Under normal conditions, applied cathodic protection current to protect deck steel does not exceed 20 mA/m^2. Thus, hydrogen evolution is highly unlikely for post tensioning strands especially if the strands receive only a small percentage of the cathodic protection current.

A transient passivation break was seen when the applied curent was between 200 and 300 mA/m^2. The reason for this is not clear but it might be caused by the variations in oxygen supply within the concrete. At the applied currrent level of 20 mA/m^2, the potential shift was about 350 mV CSE.

All the current probes received a small portion of the applied current when the duct was electrically isolated from the reinforcing steel and current probes (Figure 10). The percentage of current received by the probes decreased with increased probe distance from the anode. The probe current density ranged from only about 0.12 to 1.80 mA/m^2 at an applied anode current density of 20 mA/m^2. This indicated that most of the applied current was picked up by the deck steel and only a small percentage of current reached the probe area. Thus, hydrogen evolution at the probes is highly unlikely when the applied current is less than 20 mA/m^2.

Within the practical range of cathodic protection current, the percentage of current picked up by the probes decreased with increasing applied current (Figure 11). At higher applied current levels, however, the percentage of current received by the probes remained at about the same very low level. The reason for this behaviour is not known.

Throughout the test period, it was observed that the current received by the probes decreased with age of the concrete. This was mainly due to the increased concrete electrical resistivity with time. It is not known if this increased resistivity is caused by increased concrete hydration or a gradual drying of the beam (even though precautions were taken to reduce the possibility of drying).

The cathodic protection current was capable of altering macrocell action. Before the cathodic protection system was powered, a galvanic cell was formed with the anode at the probe embedded in the 2 % admixed chloride mortar (probe #4) and the cathode at the deck steel. As the magnitude of applied current increased, the direction of the probe current reversed as the probe gradually picked up current.

It appeared that the instant off potentials measured opposite to the current probes were not the actual potentials of the probes. The potential shifts were similar to that of the deck steel and were about 300 mV CSE as shown in Table 1. The potential readings seemed to be largely influenced by the deck steel.

3.2.2 Test 2 - Electrically connected duct

When the duct was electrically connected to the reinforcing steel and probes, the current received by the probes was negligible while the duct received a noticeable amount of current. The duct current density was approximately 2.8 mA/m², based on the area of t[illegible] steel duct, when the applied anode current density was 20 mA/m² (see Figure 12).

The negligible probe current was probably due to the shielding effect of the duct which acted as an electrical insulator to the probes and carried away most of the current distributed to the area.

In real structures, cathodic protection to deck steel would be expected to have no influence on the post tensioning strands if, as is usual, the strands and duct are electrically continuous with the reinforcing steel.

The duct current in Figure 12 was the average duct current density. The actual distribution of current over the surface area of the duct could not be determined. As shown in Table 1, the potential shifts along the profile of the duct were similar at most locations and were about 250 mV CSE when the applied anode current was about 20 mA/m². This could suggest that the current was distributed uniformly to most of the surface area of the duct. However, these potential readings might be also influenced to a large extent by the deck steel.

3.3 Pretensioned beam

3.3.1 Test 1 - Hydrogen evolution

Figure 13 presents the E log I curve for the instant off potential of deck steel and applied current. The shape of the curve was similar to that for the post tensioned beam shown in Figure 9 except there was no break near the -800 mV CSE shift. The linear portion of the curve extended up to approximately 300 mA/m² at which current the potential shift was 600 mV CSE. Hydrogen evolution hence was not likely to occur when the current level was below this very high applied current density. The potential shift was about 250 mV CSE at an applied anode current density of 20 mA/m².

Figure 14 shows the amount of current received by the current probes along the profiles of the 3 replaced strands when the applied current was about 22 mA/m^2. The probe current generally decreased with increasing probe distance from the anode. There was a wide range of probe currents which varied from about 0.2 to 6.8 mA/m^2 with an average value of 1.6 mA/m^2 at an applied anode current density of 20 mA/m^2.

Figures 15 and 16 show the potential shifts of the reinforcement at an applied anode current density of 22 mA/m^2. The data in Figure 15 were taken along a vertical line down the south side of the beam at half length. Clearly, the potential shifts decreased gradually with distance from the anode. The potential shifts of the steel in the slab all exceeded 200 mV CSE compared to about 30 mV CSE for the steel at the lower portion of the girder. Figure 16 shows the potential shifts of the reinforcement along the profiles of the current probes. The measurements were taken opposite to the probes on both sides of the beam. The data showed that the potential shifts of the reinforcement were mostly well below 200 mV CSE. The similar potential readings on both sides of the beam indicated that the applied current was distributed about evenly to the reinforcement at both sides. (It should be noted that the potentials measured on the concrete surface opposite to the probes might not be the probe potentials. Rather the half cell potentials were more likely to indicate the potentials of the steel located closest to the concrete surface where the half cell was placed. This was especially true at upper and lower portions of the girder where the probes were surrounded by a relatively large quantity of reinforcement).

The above results indicated that a large portion of the applied current was received by the deck steel and the average current picked up by the strands was small. However, probes in the upper portion of the beam picked up as much as 7.5 mA/m^2 at the applied anode current density of 22 mA/m^2 which may be a cause for concern.

Two current probes (probes #11 and 12) at the lower end of the top row did not receive current and became slightly anodic as seen in Figure 14. The probes became more anodic as the magnitude of the applied current increased. This might be mainly due to the following cause: The current distributed from the top surface of the beam was likely to take the path of least resistance (through the vicinity of the reinforcement cage). It was difficult for the current to reach those two probes from underneath since the probes were electrically isolated by the plastic strip. Macrocells could subsequently develop with the anodes at

the probes and the cathodes at the adjacent current receiving probes due to the current gradient existing between the steel. In real structures, the electrically connected strands would have better current receiving capacity than the short pieces of rebars used in this study because they would not be tied to plastic strips.

Test 1 in Table 2 shows the relationship between the currents received by 3 typical current probes and the applied current over a specific range of applied current. Similar to that in the post tensioned beam with disconnected duct, the percentage of current received by the probes decreased with increasing applied current within working range of cathodic protection current.

3.3.2 Tests 2 to 7 - Protection of prestressing strands

One of the main criteria for effective protection is the applied current should be uniformly distributed to the steel to be protected. A highly non-uniform current distribution may not only leave some of the reinforcement unprotected; it may also cause macrocell action between protected and unprotected steel as well as hydrogen evolution at the higher current zones.

The results for tests 2 to 7 are summarized in Table 3 and Figures 17 to 21.

(1) Test 2 - anode side strip with conducting polymer:

The middle row of current probes received the bulk of the applied current. This was because the anode was placed opposite to these probes and the probes were located closer to the north side (the powered side). The overall average current received by the probes was only 1.9 mA/m^2 at the applied anode current density of 47 mA/m^2 with standard deviation of 8 %. The low current percentage was probably because of the high resistance between the anode and the current probes. Many probes on the top row became anodic at higher current levels due to the uneven distribution of the applied current among the probes.

(2) Test 3 - anode side strip with conducting polymer and conducting paint:

Current distribution among the current probes improved significantly as compare to that in Test 1. The probes on

the middle row picked up a relatively large portion of the current. The overall average probe current was 5.3 mA/m² at an applied anode current densit of 19 mA/m² with standard deviation of 12 %. Two probes at both ends of the top row (probe #1 and #12) became anodic in the higher current range. It should be noted that only the current probes and their adjacent reinforcement were under protection in this case.

A test was performed to examine the influence of the reinforcement, including the prestressing strands, on the probe current. When the reinforcement was electrically disconnected from the cathodic protection system and the current probes, all the probes received significantly higher percentages of the applied current and the currents distributed among the probes were much more uniform. The result indicated that the reinforcement adjacent to the probes created an electrical shielding to the probes and carried away a large portion of the applied current distributed to the area. This effect was more obvious at the upper and lower parts of the profiles of the probes where the probes were surrounded by a large quantity of steel. In addition, it is believed that the shielding effect of the reinforcement also caused non-uniform current distribution among the probes as a result of variable reinforcement density along the girder.

(3) Test 4 - anode on north side of the girder:

Current probes on the middle row received the largest amount of current. The overall average value of probe current was 8.4 mA/m² at an applied anode current density of 21 mA/m² with standard deviation of 17 %. The current density varied from 1.7 to 18.1 mA/m². Power consumption of the system was about 0.25 watt. As seen in Figure 17, the probe at the upper end of the first row (probe #1) received only a small amount of current. This again was probably due to the shielding effect of the surrounding large quantity of reinforcing steel. This probe subseqently became anodic at higher current levels.

(4) Test 5 - anodes on top surface of the deck and on south side of the girder:

The amount of current received by the probes decreased with distance from the top surface of the beam. The overall average of probe current was 5.4 mA/m² at an applied anode current density of 20 mA/m² with standard deviation of 15 %. The probe current ranged from 1.6 to 14.8 mA/m² as shown in Figure 18. Power consumption of the system was 0.11 watt,

which was about 50 % of that in Test 4. The reduced power consumption was probably due to the decreased resistance between the anode and steel. All the probes received current over the entire test range of applied current (up to 100 mA/m^2).

Figure 19 shows the potentials measured on both the powered side and the non-powered side of the beam. The potential on the non-powered side were generally greater at the upper portion of the girder and smaller at the lower portion compared to those on the powered side. This indicated that the applied current was distributed unevenly to both sides of the beam, contrary to that in Figure 16. At the upper portion, the current was distributed from both the anode on the top surface of the deck and the anode on the powered side of the girder. According to the above result, it seems that the reinforcement near to the non-powered side received more current under this combined effect of current distribution. At the lower part of the girder, the current distributed to the reinforcement was mainly from the anode on the powered side of the girder; the reinforcement near the powered side might hence receive a larger share of the current.

(5) Test 6 - anode on both sides and end faces of the girder:

The probes on the bottom row received the larger current densities. The overall average value of probe current was about 16 mA/m^3 at an applied anode current density of 20 mA/m^2 with standard deviation of 42 %. The current ranged from 0 to 34 mA/m^2 as shown in Figure 20. Power consumption of the system was 0.29 watt. Probe #1 subsequently became anodic at higher applied current levels.

(6) Test 7 - anodes on top surface of the deck and on both sides and end faces of the girder:

The percentage of current received by the probes decreased with distance from the top surface of the beam. The overall average value of probe current was 9 mA/m^2 at an applied current density 20 mA/m^2 with standard deviation of 21 %. The current ranged from 4 to 23 mA/m^2 (Figure 21). Power consumption of the system was 0.15 watt, which was about 50 % of that in Test 6. This was probably due to the reduced electrical resistance between the anode and the ground (the open-circuit AC resistance between the anode and the ground in Test 7 was only about 30 % of that in Test 6). All the probes in Test 7 continuously received current during the whole test range of applied current (up to 100mA/m^2).

The percentage of current received by many of the probes increased with increase in applied current as given in Table 2 (Test 7). This trend was quite different than that in the cathodic protection system powered solely from the top surface of the beam (Test 1).

A test was carried out to examine the effect of moisture change on the system. The beam was wetted by hosing for a period of 20 minutes. The result showed that at a constant applied voltage the applied current increased about 10 %. Most of the probes received significantly higher current after soaking and the increase in current ranged from about 3 % to 100 %. The concrete was in a semi-moist condition prior to this test. The change in current would likely have been more drastic if the beam had been stored in outdoor environment (3).

In summary, among the various anode arrangements under study, the cathodic protection system with anodes on the top surface of the deck and on both sides of the girder (Test 7) appeared to be most effective for protecting both the deck steel and prestressing strands. The uniformity of current distribution to the reinforcement was improved considerably in this system since the applied current was distributed from the top surface of deck, as well as from both sides of the girder.

Compared to the system with anodes only on the top surface of the deck and on north side of the girder (Test 5), the overall average value of probe current in the Test 7 system increased about two-third while the power consumption increased only by about one-third.

3.4 Hydrogen evolution

Figure 22 shows the evolution rate of hydrogen within the test range of polarized potentials. It should be noted that a small quantity of hydrogen was also generated at about -780 mV CSE over the test period. However, the actual mass of hydrogen could not be determined due to the accuracy of the instrument.

The curve in Figure 22 appeared to be asymmetric. The rate of increase in hydrogen evolution was relatively high at potential levels above -950 mV CSE and was small at potential levels below -840 mV CSE. By extrapolating the test data, the potential level for the onset of hydrogen evolution was probably between -750 mV and -800 mV CSE. This potential level appeared to be lower (more positive)

than the potential levels indicated by the E log I curves for the two test beams (Figures 9 and 13). It should be noted that the test specimen in this study was immersed in saturated lime solution. The diffusion rate of oxygen to the cathode surface, therefore, was considerably lower than that in the moist concrete. This might have a significant influence on the polarized potential of steel.

The actual mass of hydrogen generated was about 30 % of the theoretical maximum value which would have been formed if all the electrical energy had been used to produce hydrogen according to the reaction:

$$2\ H_2O + 2\ e^- \rightarrow 2\ OH^- + H_2$$

This value of 30 % of the current being consumed in the production of hydrogen was more or less independent of the polarized potential within the limit of the relatively crude experiment performed.

4. CONCLUSIONS

Test results of this investigation showed that:

1. Cathodic protection of the deck steel in the post tensioned beam had no adverse effect on the post tensioning strands under normal operating condition.

2. Cathodic protection could not be used to protect the post tensioning strands in the post tensioned beam in which the metal duct was electrically connected to the reinforcing steel.

3. Cathodic protection of the deck steel in the pretensioned beam was unlikely to have an adverse effect on the prestressing strands when the applied current did not exceed 20 mA/m^2. At this current density the maximum potential shift of the prestressing steel was not more than 200 mV CSE.

4. Caution should be exercised if cathodic protection is to be used to protect prestressing steel in pretensioned beams. Uniform distribution of cathodic protection current to the reinforcement is difficult to obtain. Satisfactory performance might be possible only when an anode is placed on the entire top surface of the beam and on both sides of the girder.

5. Under the conditions of the relatively crude experiment carried out, the potential level for the onset of hydrogen evolution was about -850 mV CSE, which was much less negative than that previously realized.

REFERENCES

1. Vrable, J. B., "Cathodic Protection for Reinforcing Steel in Concrete," Chloride Corrosion of Steel in Concrete," ASTM STP 629, D.E. Tonini and S.W. Dean,Jr., Eds., American Society for Testing and Materials, 1977, pp.124-149.

2. Stratfull, R.F., "Criteria for the Cathodic Protection of Bridge Decks," Corrosion of Reinforcement in Concrete Structures, A.P. Crane, Ed., Society of Chemical Industry, U.K., 1983, pp. 287-331.

3. Schell, H.C., Manning, D.C., and Clear, K.C., "Cathodic Protection of Bridge Substructures - Burlington Bay Skyway Test Site, Initial Performance of Systems 1 to 4," MTC Report ME-83-05.

Table 1. Post tensioned beam - potential shift

Probe location #	Disconnected duct		Connected duct	
	Initial potential (-mV CSE)	Potential shift (mV CSE)	Initial potential (-mV CSE)	Potential shift (mV CSE)
0*	130	300	220	270
1	190	300	240	220
2	210	290	240	240
3	190	300	230	250
4	200	290	240	250
5	190	300	230	250
6	160	300	210	240
7	180	290	220	250

*0 - Top surface of the beam

Note: applied current 20 mA/m^2

Table 2. Pretensioned beam - relationship between probe current and applied current

Test* #	Applied current (mA/m^2)	Probe current / Applied current (%)		
		#13	#19	#23
1	10	12	7.8	3.4
	22	11	6.0	2.9
	30	9.1	5.4	2.5
	42	7.7	4.6	1.9
	62	6.2	3.7	1.7
7	9.2	54	62	55
	20	39	46	36
	31	36	44	29
	40	39	44	27
	59	51	46	24

*1 - Anode located on the top surface of the beam

7 - Anode located on the top surface of the beam and on both sides of the girder

Table 3. Pretensioned beam, Tests 1 to 6 - average probe current

Test #	Applied current (mA/m^2)	Current probe*	Mean (%)+	Standard deviation (%)+
2	47	T	2.7	4.1
		M	5.6	13
		B	3.8	3.8
		Total	3.9	8.2
3	19	T	23	11
		M	32	13
		B	29	11
		Total	28	12
4	21	T	34	17
		M	45	17
		B	41	18
		Total	40	17
5	20	T	35	20
		M	26	9.4
		B	21	7.4
		Total	27	15
6	20	T	76	50
		M	80	37
		B	90	38
		Total	82	42
7	20	T	55	29
		M	41	15
		B	38	14
		Total	45	21

*T - Top row; M - Middle row; B - Bottom row

+% of the applied current

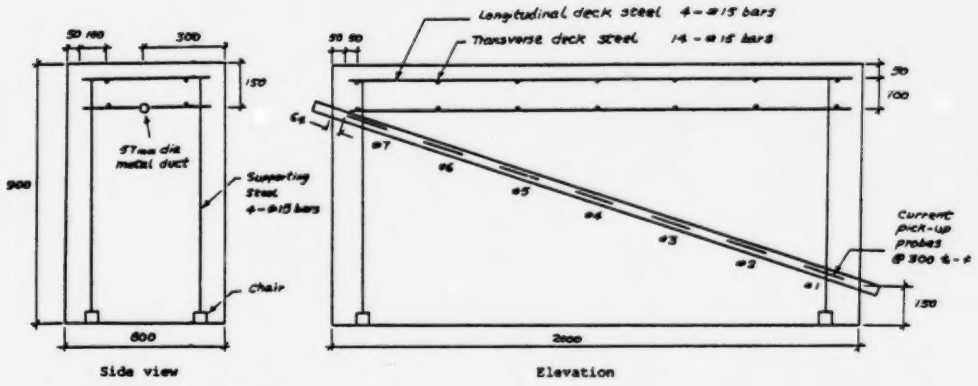

Figure 1a/ Post Tensioned Beam – Schematic Drawing, Elevation and Side View

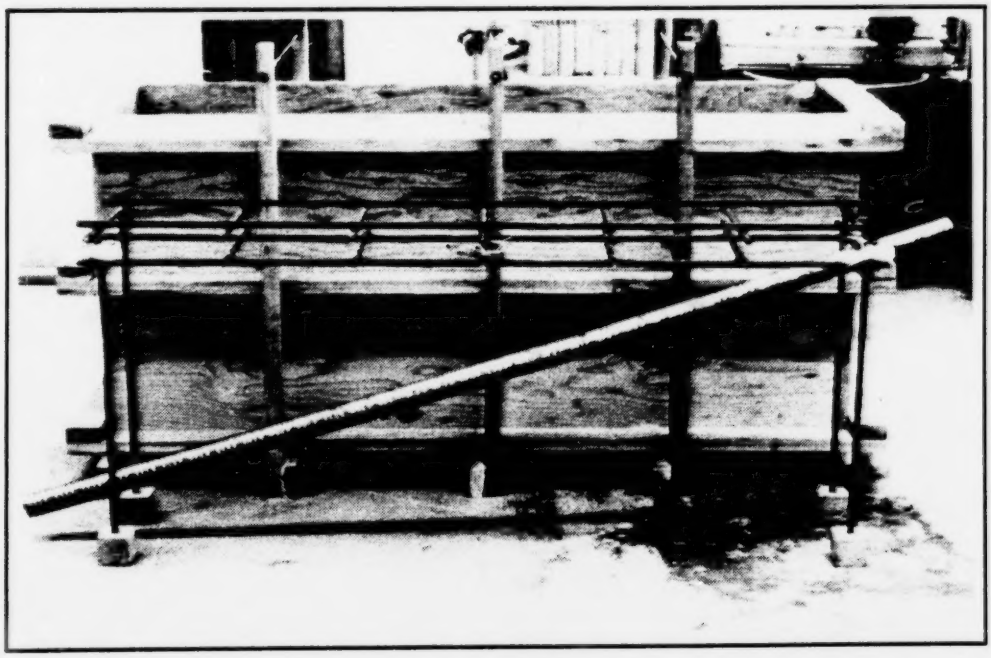

Figure 1b/ Post Tensioned Beam – Reinforced Cage

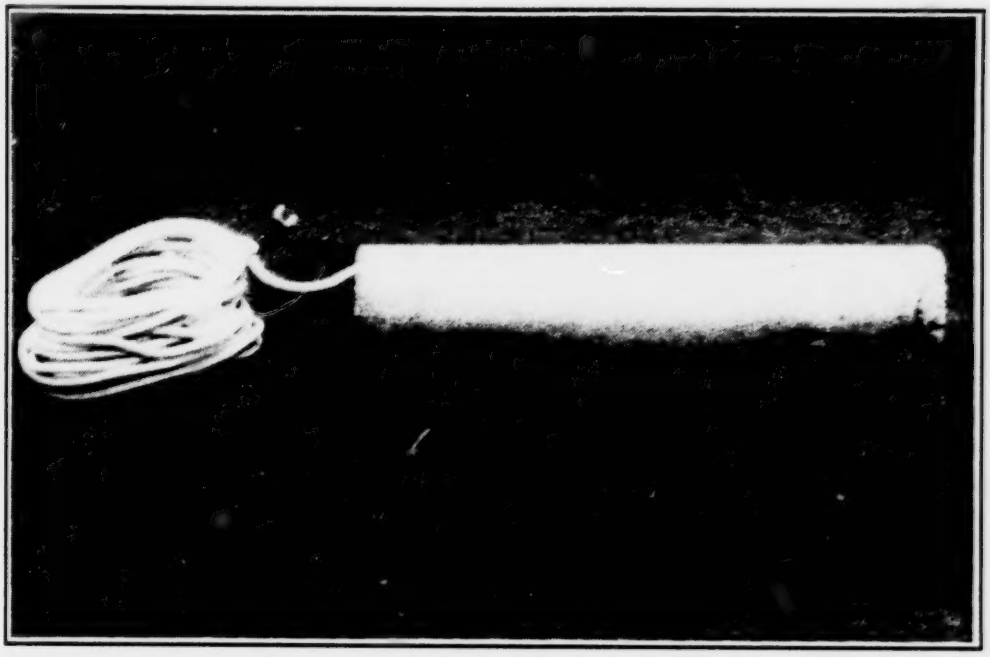

Figure 2/ Post Tensioned Beam – Current Probe

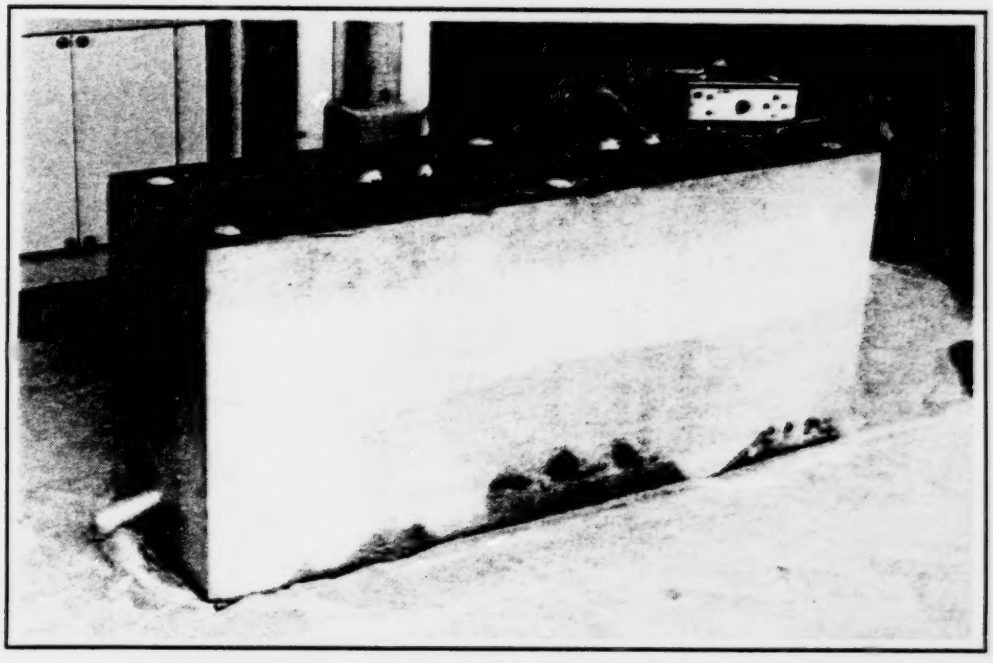

Figure 3/ Post Tensioned Beam – Complete Beam

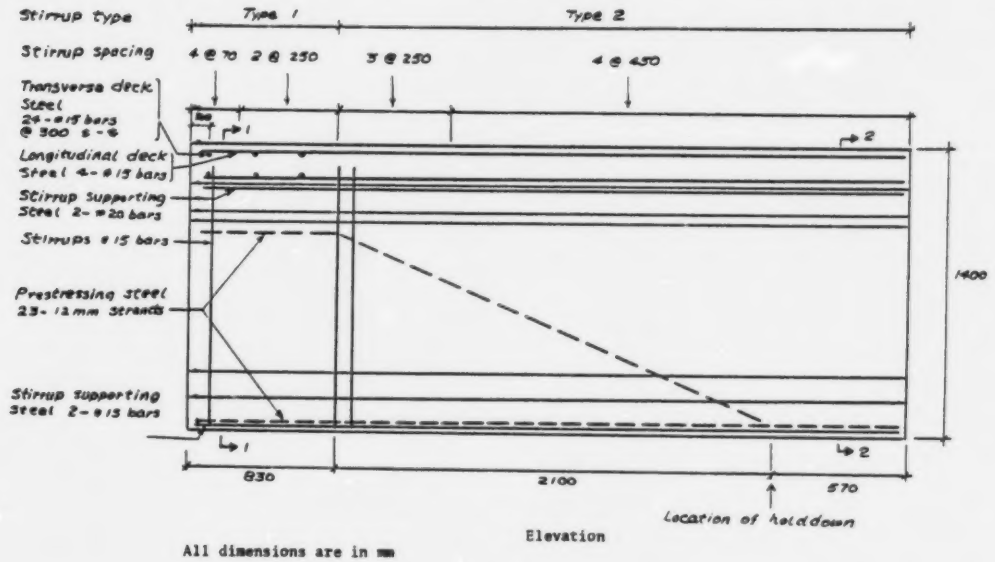

Figure 4a/ Pretensioned Beam – Schematic Drawing, Elevation

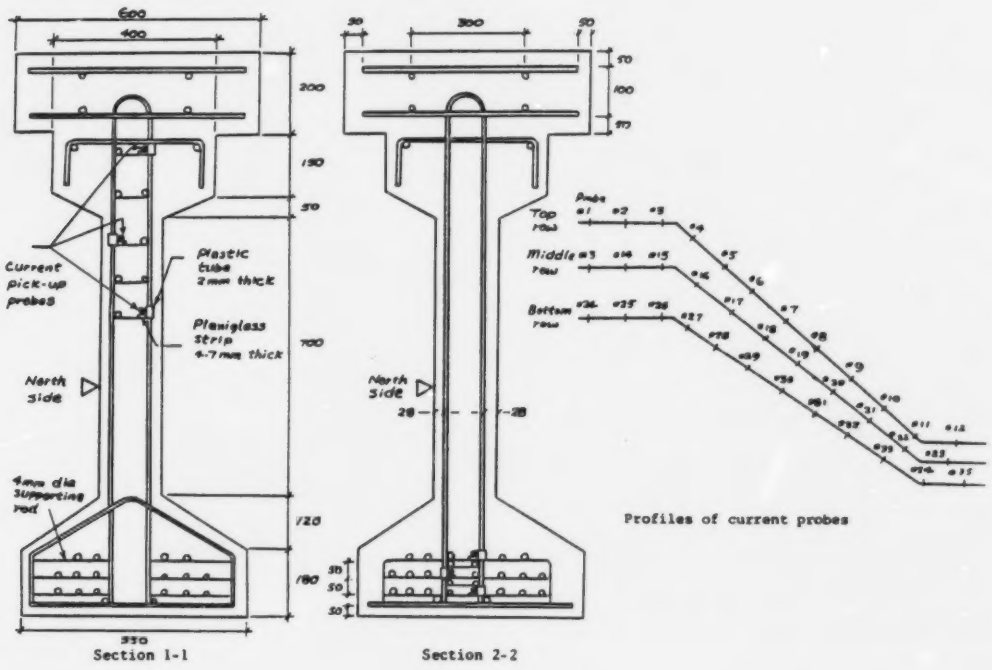

Figure 4b/ Pretensioned Beam – Schematic Drawing, Sections 1-1 and 2-2

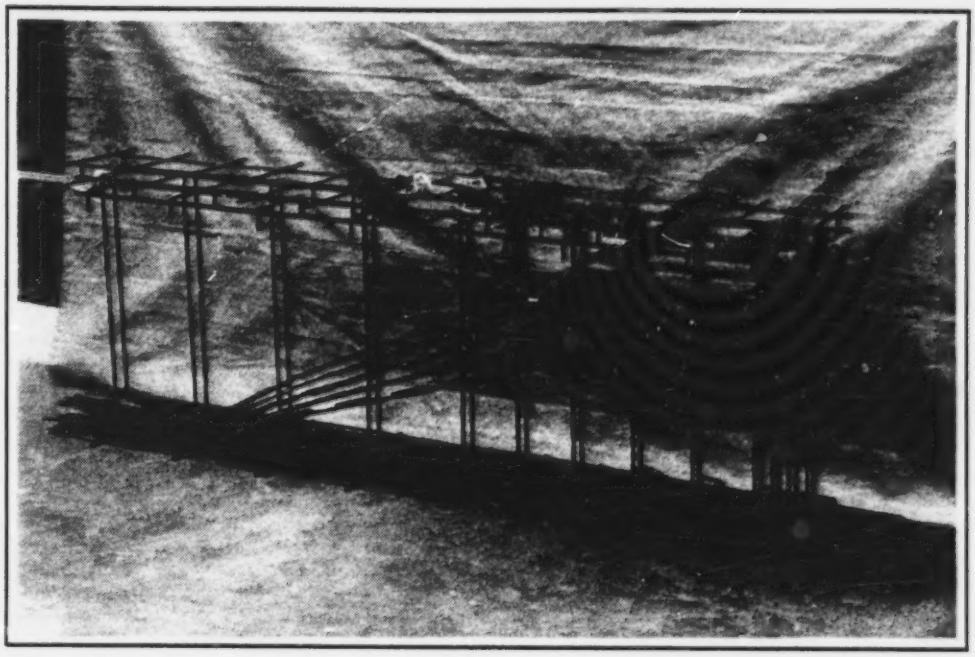

Figure 4c/ Pretensioned Beam – Reinforced Cage

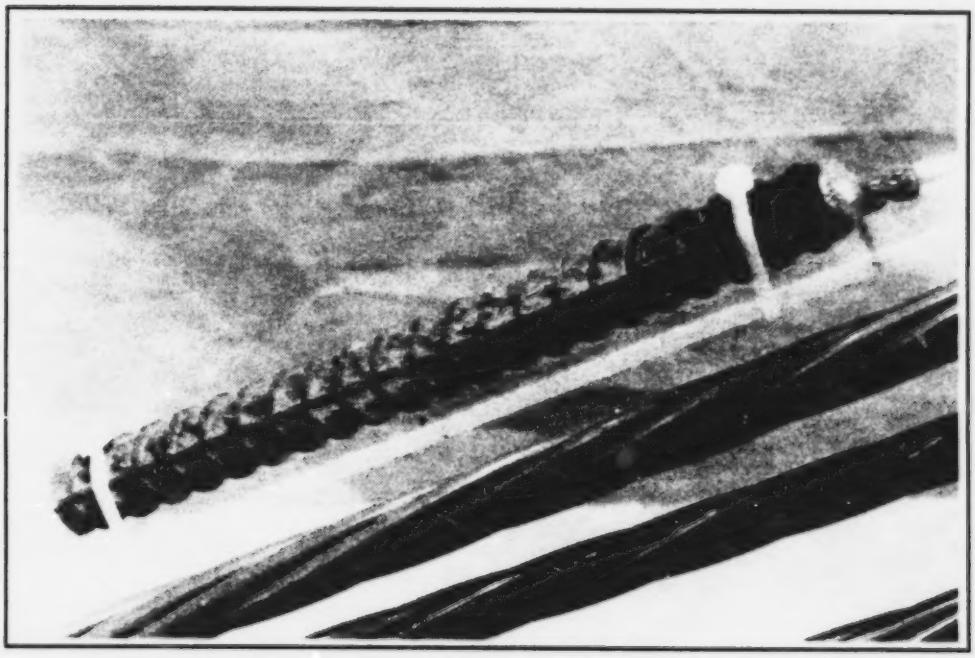

Figure 5/ Pretensioned Beam – Current Probe

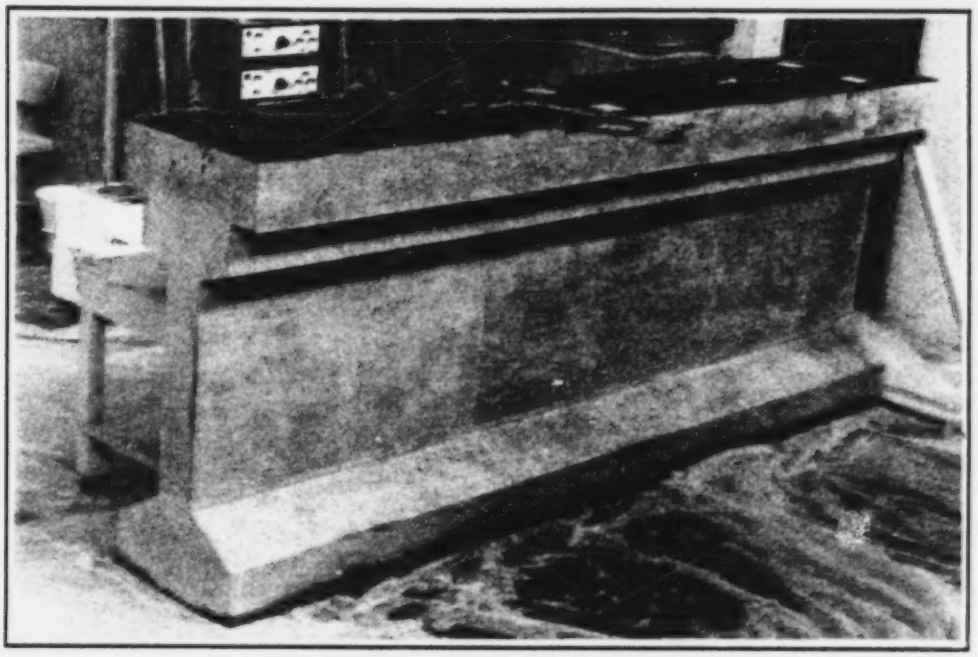

Figure 6/ Pretensioned Beam – Complete Beam

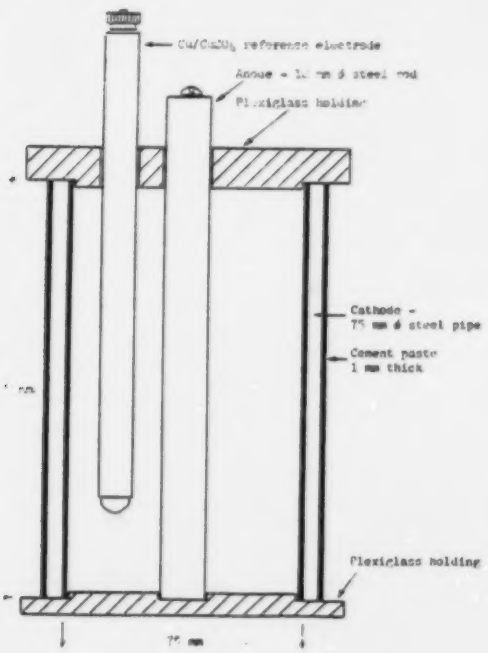

Figure 7/ Cross-section of Cell Used for Determination of Hydrogen Evolution

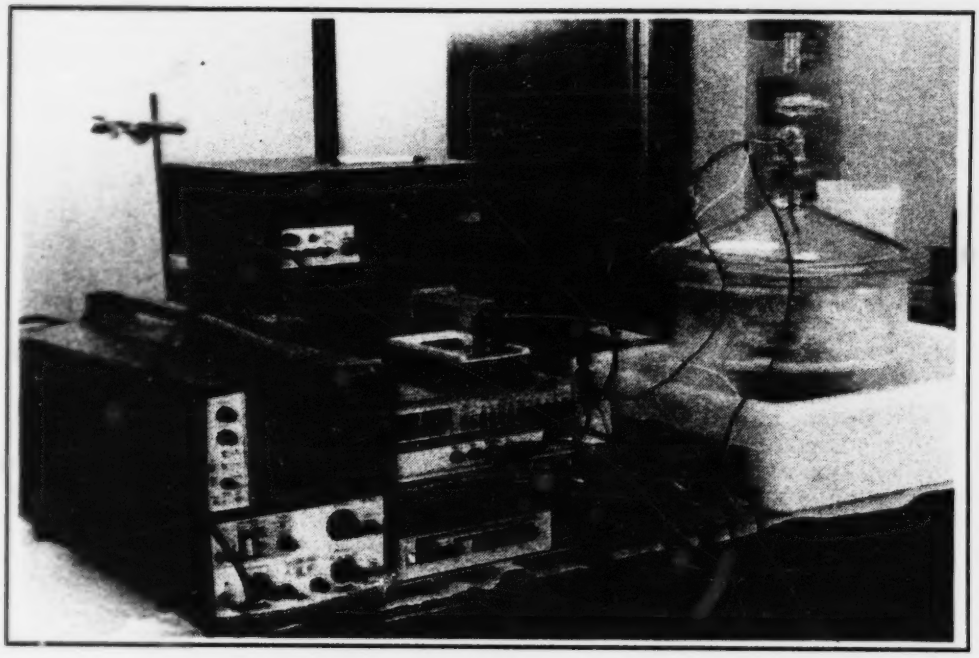

Figure 8/ Test Arrangement for Determination of Hydrogen Evolution

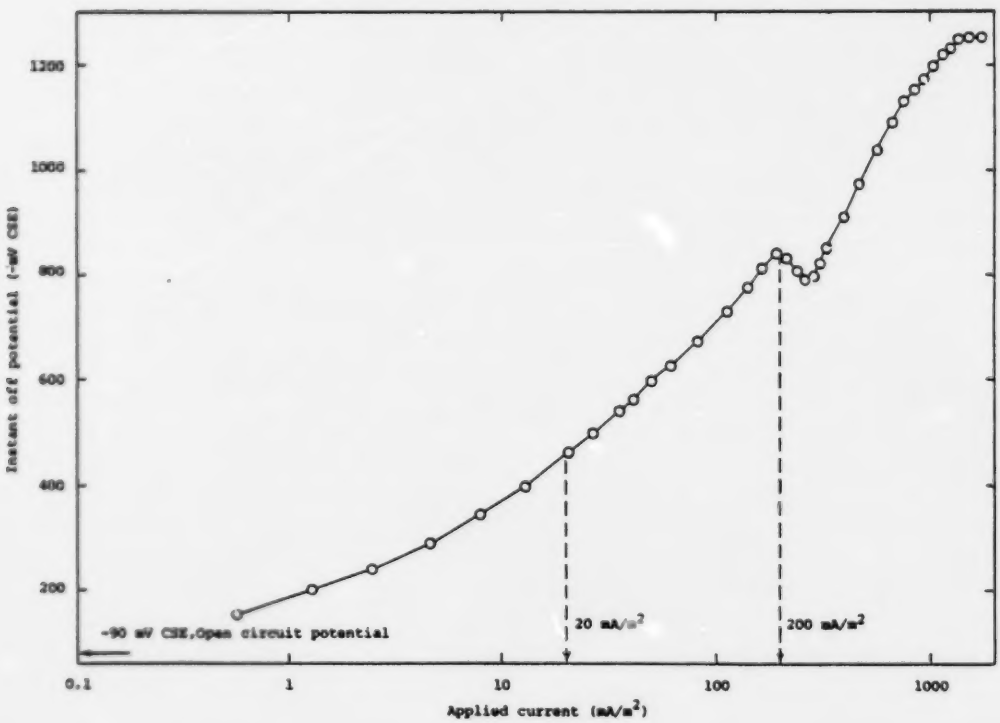

Figure 9/ Post Tensioned Beam – E log I Curve

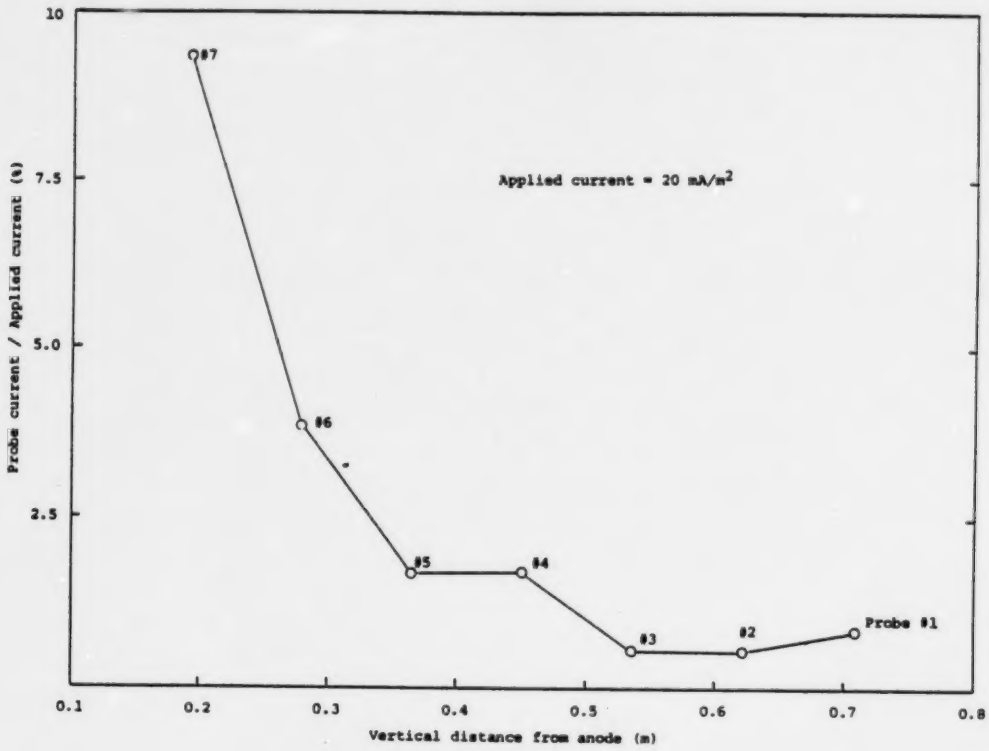

Figure 10/ Post Tensioned Beam, Electrically Isolated Duct – Probe Currents

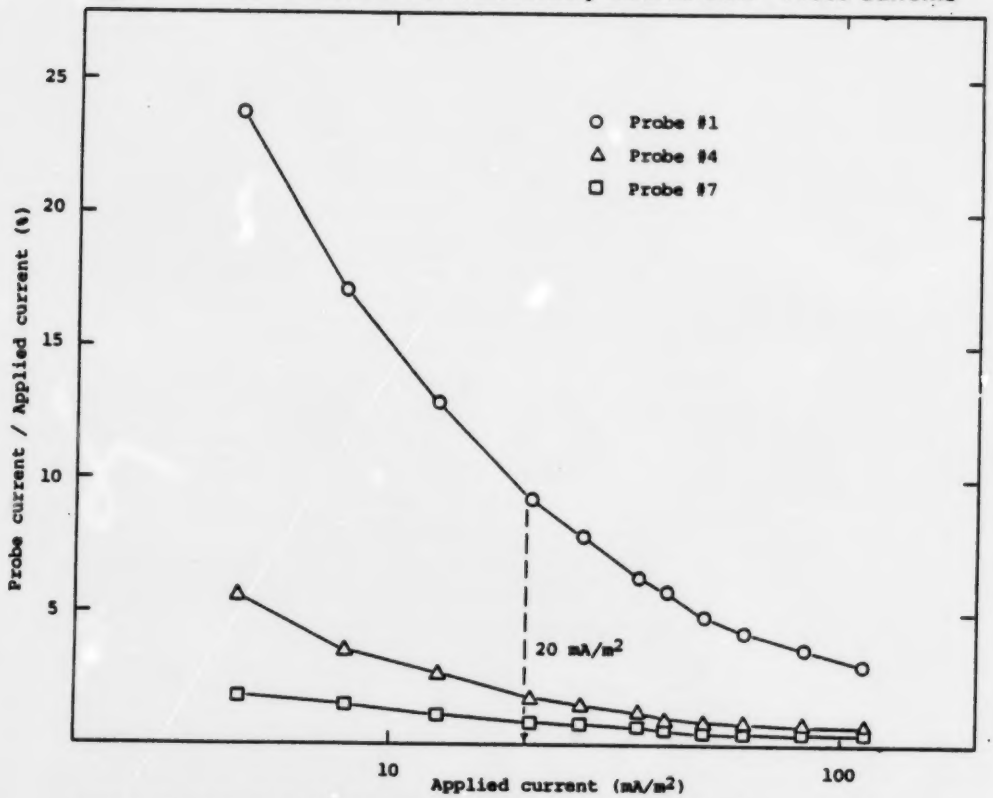

Figure 11/ Post Tensioned Beam, Electrically Isolated Duct – Relationship Between Probe Current and Applied Current

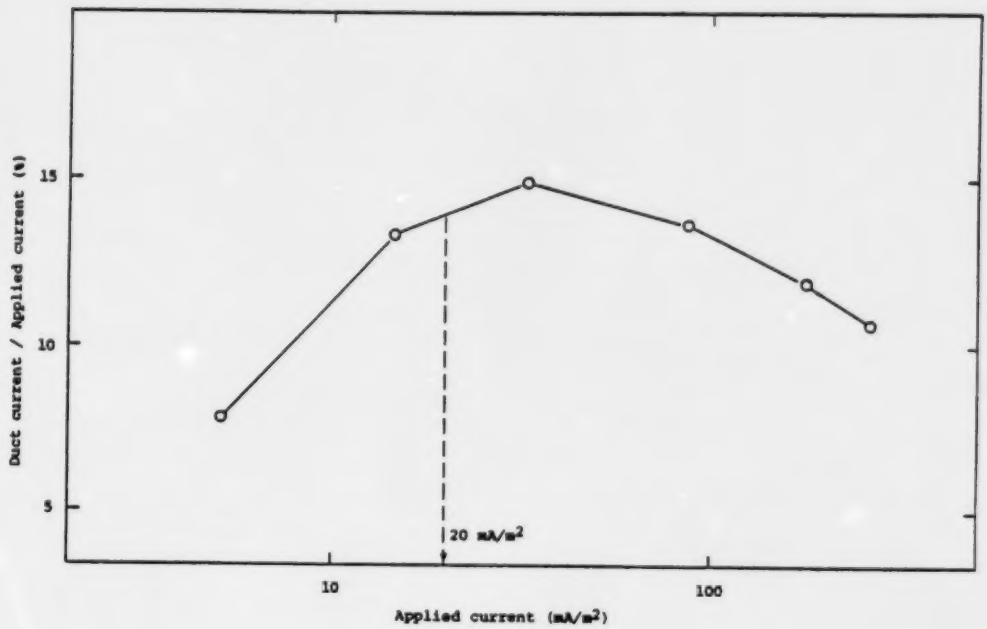

Figure 12/ Post Tensioned Beam, Electrically Connected Duct – Duct Current

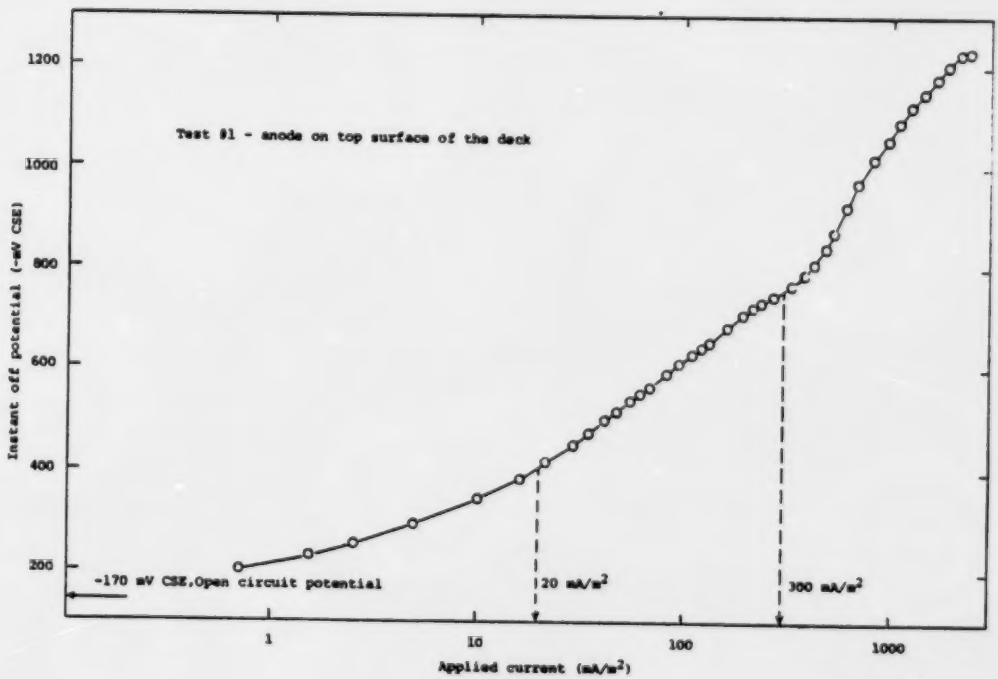

Figure 13/ Pretensioned Beam, Test No. 1 – E log I Curve

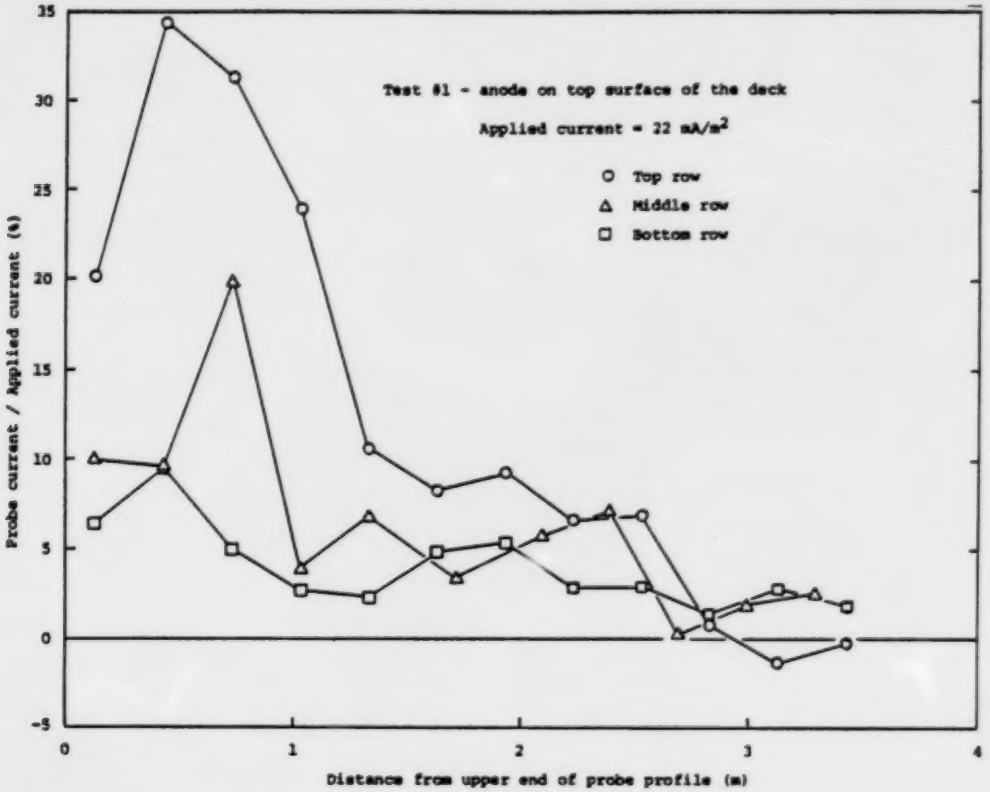
Test #1 - anode on top surface of the deck
Applied current = 22 mA/m²
Top row
Middle row
Bottom row
Probe current / Applied current (%)
Distance from upper end of probe profile (m)

Figure 14/ Pretensioned Beam, Test No. 1 – Probe Currents

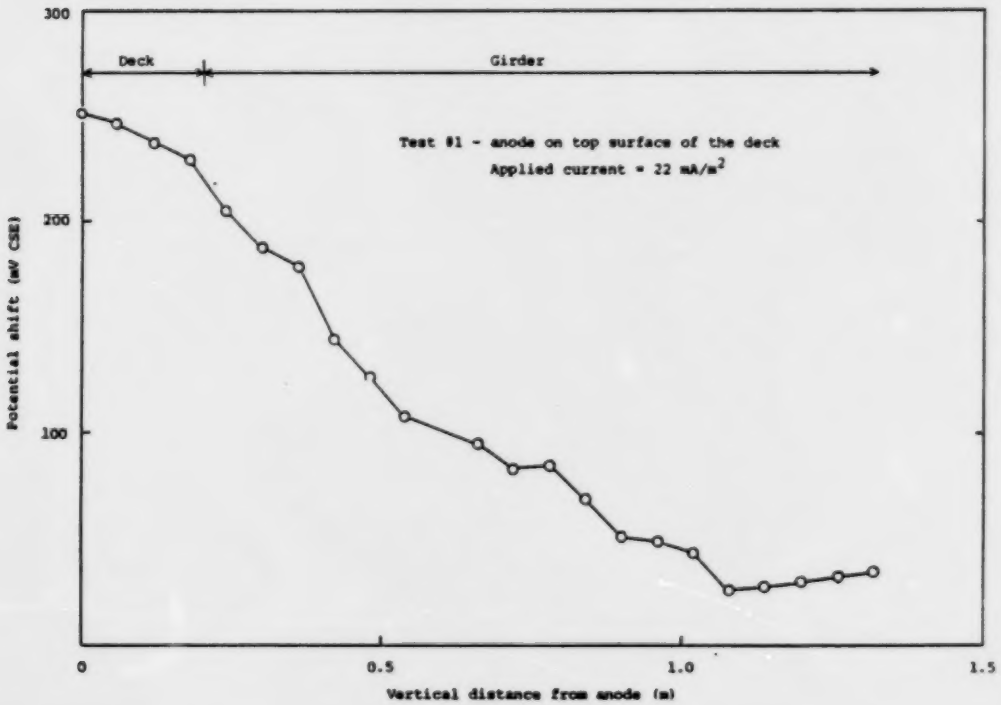
Deck
Girder
Test #1 - anode on top surface of the deck
Applied current = 22 mA/m²
Potential shift (mV CSE)
Vertical distance from anode (m)

Figure 15/ Pretensioned Beam, Test No. 1 – Potential Measurements Along a Vertical Line Down the South Side of the Beam

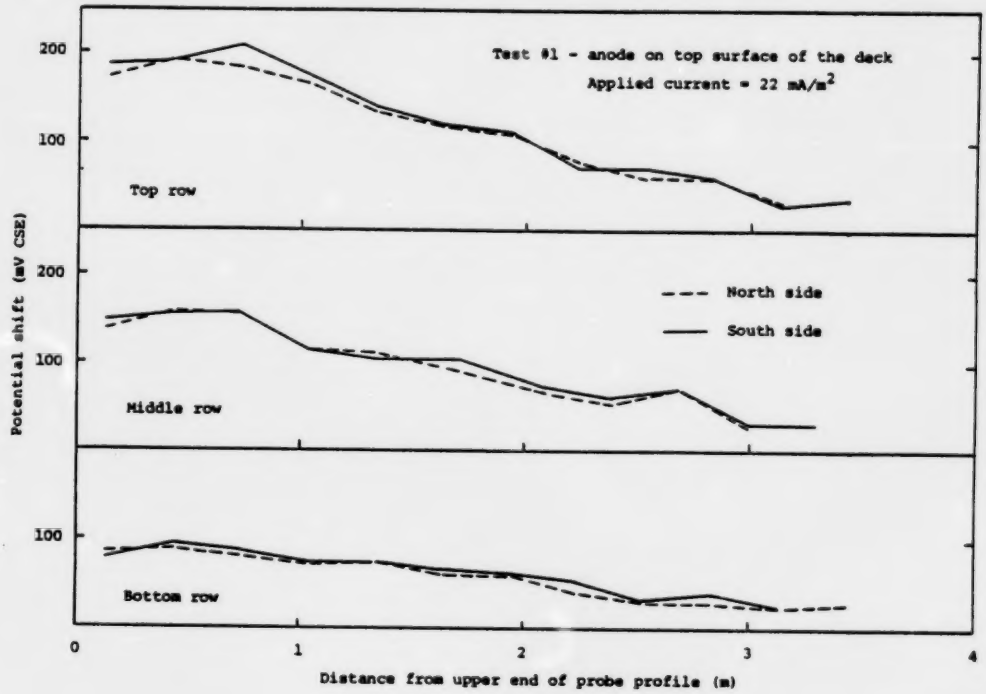

Figure 16/ Pretensioned Beam, Test No. 1 – Potential Measurements Along Profiles of Current Probes on Both Sides of the Beam

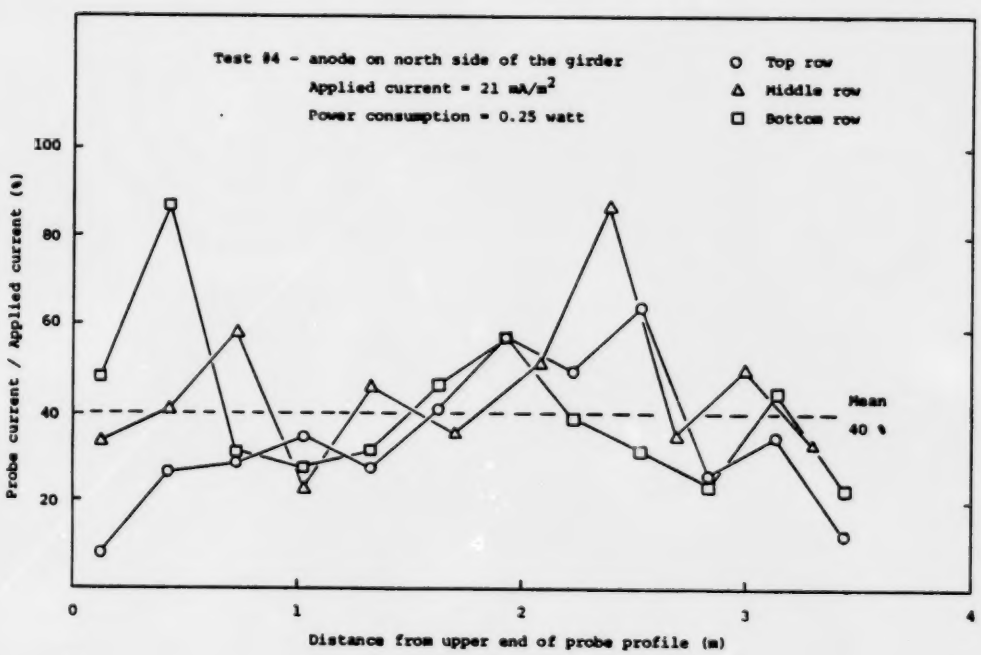

Figure 17/ Pretensioned Beam, Test No. 4 – Probe Currents

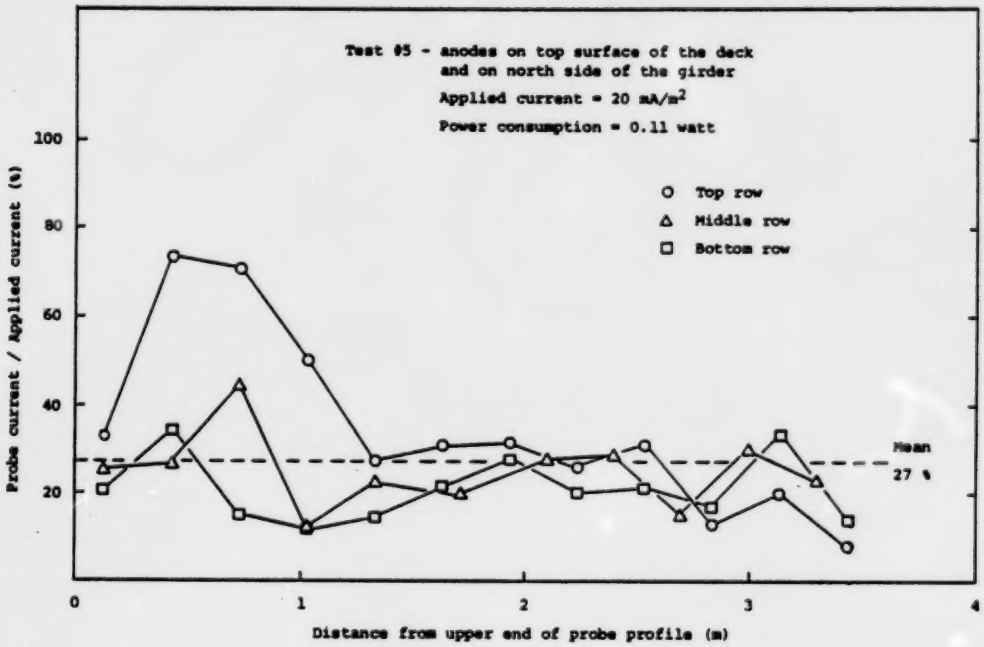

Figure 18/ Pretensioned Beam, Test No. 5 – Probe Currents

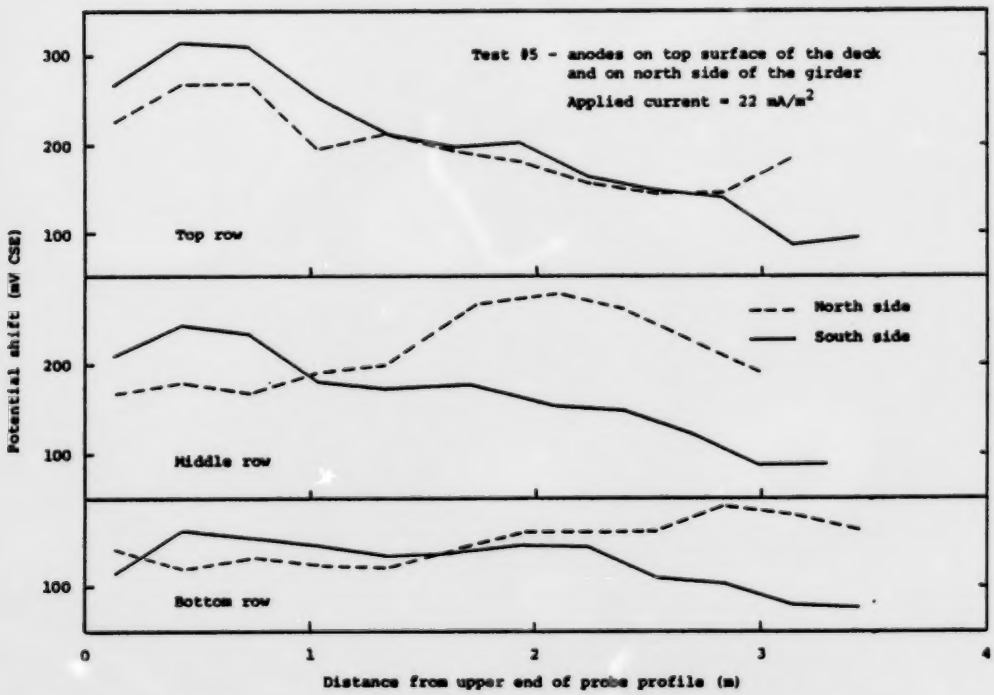

Figure 19/ Pretensioned Beam, Test No. 5 – Potential Measurements Along Profiles of Current Probes on Both Sides of the Beam

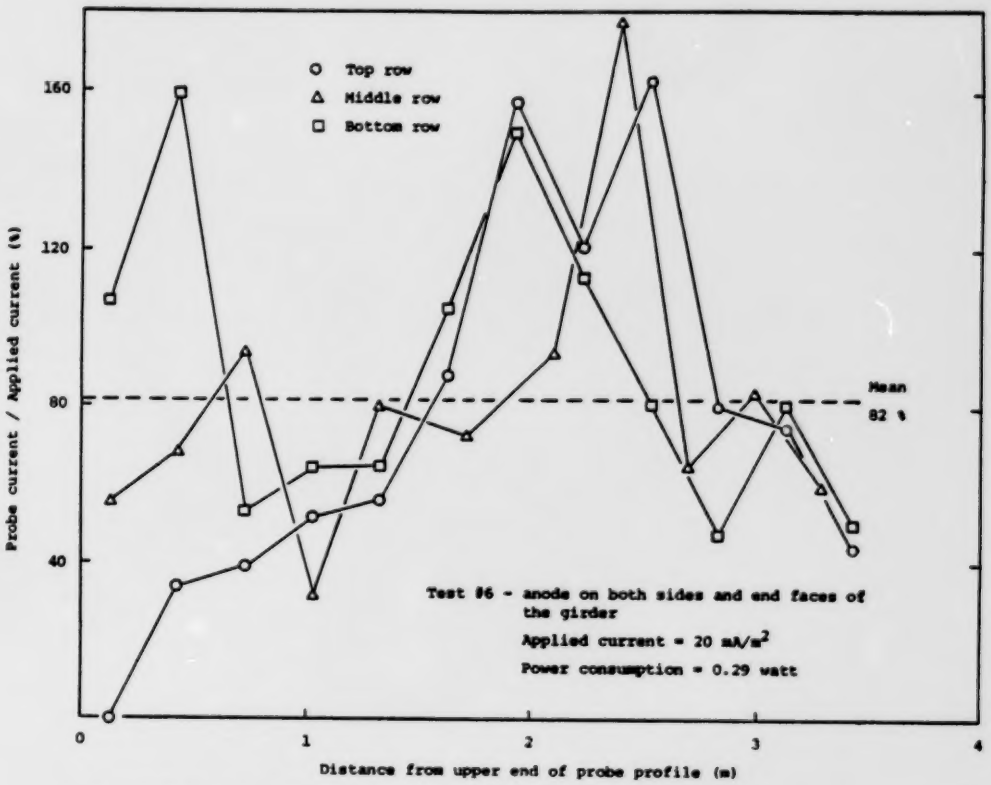
Top row
Middle row
Bottom row
Mean
82 %
Test #6 - anode on both sides and end faces of the girder
Applied current = 20 mA/m²
Power consumption = 0.29 watt
Probe current / Applied current (%)
Distance from upper end of probe profile (m)

Figure 20/ Pretensioned Beam, Test No. 6 – Probe Currents

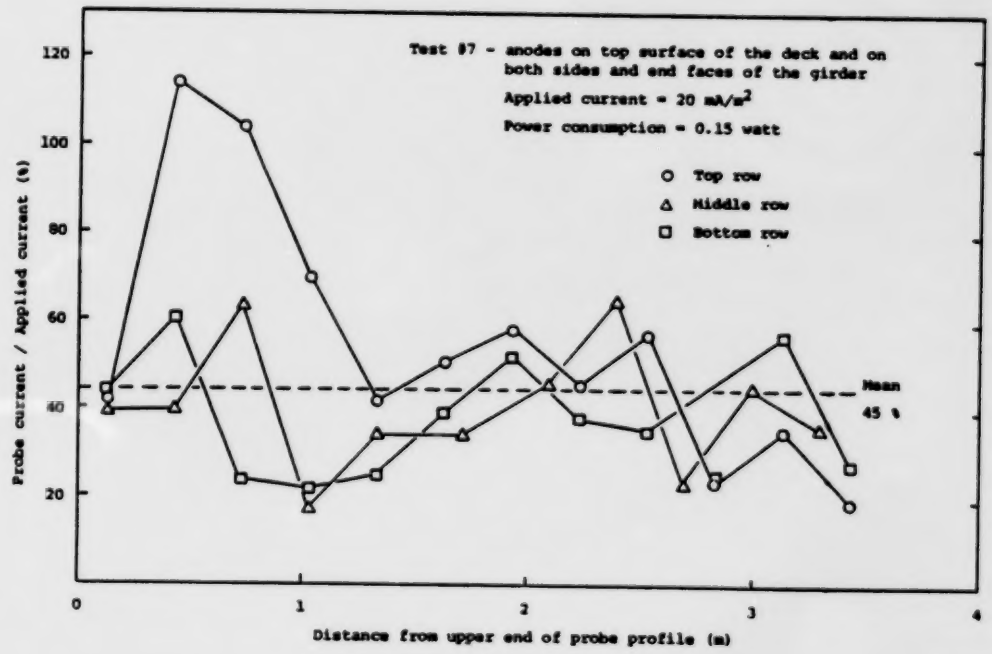
Test #7 - anodes on top surface of the deck and on both sides and end faces of the girder
Applied current = 20 mA/m²
Power consumption = 0.15 watt
Top row
Middle row
Bottom row
Mean
45 %
Probe current / Applied current (%)
Distance from upper end of probe profile (m)

Figure 21/ Pretensioned Beam, Test No. 7 – Probe Currents

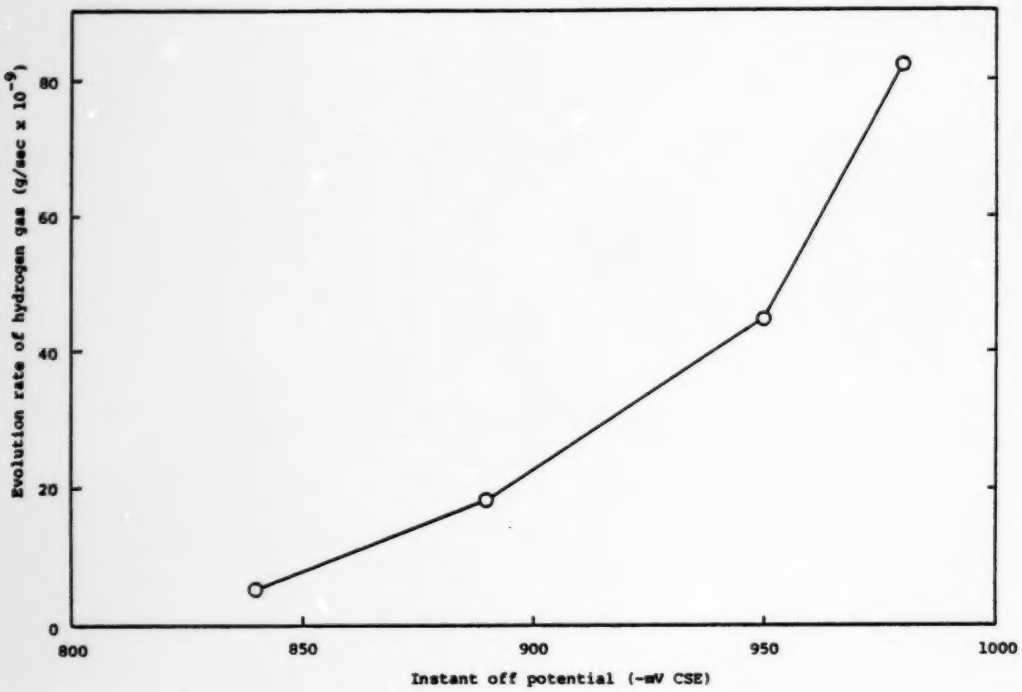

Figure 22/ Evolution Rate of Hydrogen Gas